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Binding energy of donor impurities in double inverse parabolic quantum well under electric field

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ABSTRACT

In this study, effects of the electric field applied along the growth direction on the binding energy of donor impurities in double inverse parabolic quantum well (DIPQW) with different well and barrier widths, as well as different Al concentrations in the center of the wells have been investigated. The Al concentration at the barriers was always $x_{max} = 0.3$. The calculations were performed within the effective mass approximation, using a variational method.

1. Introduction

Multiple quantum well semiconductor heterostructures are important candidates for technological applications. Basically, technological applications of multiple quantum well semiconductor systems depend on their optical and transport properties that are determined by wells and barriers-widths, as well as on the quality of their interfaces. Double quantum wells have attracted a great deal of interest recently because of their potential applications as opto-electronic devices (e.g., photo-detectors, electro-optical switches and tera-Hertz oscillators [1–16]). With the development of molecular-beam epitaxy growth method, quantum wells can be made into different forms, such as double square, triangular or graded and parabolic quantum wells [17–19]. Such structures, rather than having a conventional square potential, present desirable optical features for devices design and favorable "Stark shift" characteristics, which can be used to control and modulate the intensity output of the devices. Furthermore, in addition to the potential profiles mentioned above the binding energies of hydrogenic impurity states and excitons, interband absorption and density of states of impurities in an inverse parabolic qantum well under the electric and magnetic fields have been studied [20,21].

External fields have become an effective tool for studying the physical properties of low-dimensional systems, both from the theoretical and the technological point of views. Application of an electric field in the growth direction of the system causes polarization of carrier distribution and shifts the quantum energy states. These effects cause considerable changes in the energy spectrum of the carriers, which may be used to control and modulate the intensity output of devices [22].

In this work, we report on the effects of electric field on the binding energy of the hydrogenic donor impurities in double inverse parabolic quantum well (DIPQW) with different well and barrier widths, as well as different Al concentrations at the well center. Al concentration, at the barriers was always $x_{max} = 0.3$. The schematic representation of DIPQW for different Al concentrations (i.e. $\sigma = 1.5$ ($x_c = 0.2$), 3 ($x_c = 0.1$) and 6 ($x_c = 0.05$)) at the well center is given in Fig. 1.

2. Theory

Within the framework of an effective mass approximation, the Hamiltonian of a hydrogenic donor impurity in double inverse GaAs/$Ga_{1-x}Al_xAs$ parabolic quantum well in the presence of electric field, can be written as

$$H = \frac{p^2}{2m_e^*} + V(z_e) - \frac{e^2}{\varepsilon_0|\vec{r}_e - \vec{r}_i|} + eFz, \quad (1)$$

where $m_e^*(= 0.067m_0$, where m_0 is the free electron mass) is effective mass, e is elementary charge, $\vec{p}$ is momentum, $\varepsilon_0(= 12.5)$ is dielectric constant, $\vec{r}(= \vec{r}_e - \vec{r}_i)$ is the distance between the

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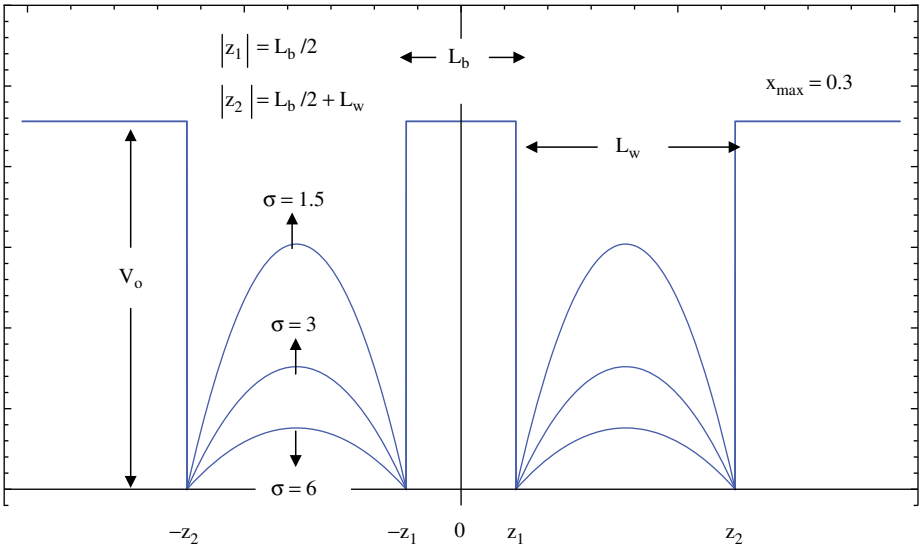

Fig. 1. Schematic representation of DIPQW for different Al concentrations in the well centers (wc).

carrier and the donor impurity site and $V(z)_e$ is confinement potential profile for electron in z-direction.

The functional form of confinement potential is given by

$$V(z_e) = \begin{cases} V_0, & |z| > z_2 \\ \dfrac{4V_0}{\sigma}\left(\dfrac{(z_1-|z|)(z_2-|z|)}{(z_1-z_2)(z_2-z_1)}\right), & z_1 \leqslant |z| \leqslant z_2 \\ V_0, & |z| \leqslant z_1 \end{cases} \quad (2)$$

where $\sigma = (x_{max}/x_c)$ (x_{max} is constant Al concentration at barriers, x_c is Al concentration at the well center), $V_0(=228\,\text{meV})$ is band discontinuity for $x_{max} = 0.3$ and $(4V_0/\sigma)$ is the maximum value of potential at the well center.

We choose the trial wave function as a product of the three-dimensional wave function in the Coulomb potential are ground state wave function of the DIPQW:

$$\Psi(\rho, z) = N\psi(z)\exp\left[-\sqrt{\frac{\rho^2}{\lambda^2}+\frac{(z-z_i)^2}{\beta^2}}\right] \quad (3)$$

where N is normalization constant and λ and β are the variational parameters. The ground-state impurity energy is evaluated by minimizing the expectation value of the Hamiltonian in Eq. (1) with respect to λ and β.

Ground-state donor binding energy is calculated by

$$E_b = E_z - \min_{\lambda,\beta}\langle\Psi|H|\Psi\rangle \quad (4)$$

where E_z is the ground-state energy of electron obtained from Schrödinger equation in the z-direction without the impurity.

3. Results and discussion

In Fig. 2, binding energies of donor impurities located in the center of wells (wc) and in the barrier center (bc) of DIPQW in the absence of the electric field, versus well widths for different Al concentrations in the wc are given for (a) $L_b = 25$ Å and (b) $L_b = 50$ Å. Dashed lines correspond to the double square quantum well (DSQW). As well width increases, binding energy decreases for all impurity positions since the probability of finding electron and impurity in the same plane decreases. This is a consequence of decreasing the geometric confinement. But as Al concentration at the center of the wells decreases, binding energies increase for impurities located in the well centers (for $F = 0$, the probability of finding electron in both wells is the same) while it decreases for impurity located in the bc. Thus for DSQW, binding energy for impurity located in wc (in bc) becomes larger (smaller) than that of DIPQW. As seen in Fig. 2(b), as the coupling between wells decreases ($L_b = 50$ Å), probability of finding the electron in the barrier (in the wells) decreases (increases). As known, as the barrier width increases, effective length—$L_{eff} = L_1+L_b+L_2$—($L = L_1 = L_2$) increases and the Coulombic interaction between electron and donor impurity decreases, and so the binding energy for impurity located in wc (in bc) becomes larger (smaller) than that of Fig. 2(a).

In Fig. 3, the variation in binding energies of donor impurities located in the left well center (lwc), in the barrier center (bc) and in the right well center (rwc) of DIPQW under the electric field, versus the well widths for different Al concentrations in the wc are given for (a) $L_b = 25$ Å and (b) $L_b = 50$ Å, respectively. Dashed lines correspond to DSQW.

When the electric field is applied, degeneracy is broken. The Coulombic interaction between electron and donor impurity located in the barrier center or the right well center decreases, while it increases for impurity located at the left well center, since electrons shift to the left side of the structures. As seen in these figures, the field dependence of binding energy in narrow well dimensions is weak, since the geometric confinement is predominant. But in the wider quantum wells, binding energy is more sensitive to external electric field.

4. Conclusion

As summary: the effects of the electric field, which is applied along the growth direction on the binding energy of donor impurities in double inverse parabolic quantum well with different well and barrier widths, as well as different Al concentrations, in the center of the wells have been investigated. The calculations were performed within the effective mass approximation, using a variational method. Obtained results show that by changing the Al concentrations in the center of the wells together with the electric field and the structure parameters, such as well and barrier widths, desired energy range or spectral range of interest, intersubband and also interband absorption peak position may be tuning. This tunability gives a possibility for near-infrared electro-absorption modulators and quantum well infrared detectors. To the best of our knowledge, this is the first study